RESIDUAL STRESS DISTRIBUTION AND ITS INFLUENCE ON THE MECHANICAL BEHAVIOUR OF COMPOSITE LAMINATES

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SUMMARY

The objective of this study is to investigate the influence of residual stresses due to fabrication conditions on the mechanical behavior of laminate structure. Firstly, we have fabricated the laminate $[0_2 /90_2]_s$ from unidirectional carbon/epoxy prepreg (T300/914) with three different cooling conditions (fast, normal and slow). And then the residual stress distribution in laminates was measured by using the incremental hole-drilling method and was calculated by a finite element model. Finally, specimens cut from these laminates were tested in tension test to obtain their tension strength. It is showed that cooling condition in forming process plays an important part in residual stress distribution in laminates. The latter has to be taken into account for strength prediction of laminate structures.

KEYWORDS : residual stress, forming process, mechanical behaviour, finite element analysis.

INTRODUCTION

The mismatched coefficients of thermal expansion (CTE) in thermosetting composite laminates produce some residual stresses during fabrication, especially between the adjacent plies 0° and 90°. Sometimes, these residual stresses can reach the values comparable to the transverse tension strength and interphase shear strength of composite element ply. Furthermore, the expansion due to moisture absorption can also bring non-uniform residual stresses in a given ply of a laminate. The existence of residual stresses, combined with mechanical loads, could decrease considerably the durability of laminate structure by provoking matrix cracking, delamination, debonding and breaking of fibers [1, 2].

Residual stresses in a laminate induced by forming process depend on many relevant parameters, such as : material properties, cooling conditions and post moisture absorption [3]. Theoretical predictions and numerical simulations may deviate from the real residual stress values. Thus, it is necessary to measure them by experimental methods so as to verify theoretical results as well as to provide a reliable means of residual stress determination. The embedded strain gage method was developed by Daniel & al [4] to investigate the residual stresses in laminated composites. By preplacing crystalline filler particles into matrix, the X-ray diffraction method was successfully applied by Predecki [5] and Fenn [6] to non-crystalline materials. These methods were extremely helpful in investigating the mechanism of residual stress formation but they are unsuitable to detect residual stresses of the post-procedure in a real composite product. Wu and Lu [7-9] have proposed a new method using the combined technique of moiré interferometry and incremental hole drillings. This new technique features high sensitivity and allows to determine with accuracy residual stresses in each ply of a laminate. Other experiments such as first ply failure test and curvature measurement were also used in the literature [10].

In the present work, the hole-drilling method is used to measure experimentally, ply by ply, residual stresses in laminates, herein the finite element simulation is proved a useful tool .

MATERIALS & COOLING CONDITIONS

The materiel used in this study is a composite carbon-epoxy T300/914. The laminates were prepared from 8 plies unidirectional prepreg ((V_f= 60%, 8 plies = 1 mm), such a thickness ensures laminates to have a uniform temperature during cooling process. The stack sequence of laminates studied is $[0_2 /90_2]_S$. Elastic constants and strengths of unidirectional laminate of this material [16] are presented in table 1.

Table 1 : Elastic constants of unidirectional T300/914

E_{11} (GPa)	E_{22} (GPa)	E_{33} (GPa)	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)	υ_{12}	υ_{13}	υ_{23}
131.90	9.51	9.43	5.27	7.03	3.39	0.33	0.34	0.49
X^+ (MPa)	X^- (MPa)	Y^+ (MPa)	Y^- (MPa)	Z^+ (MPa)	Z^- (MPa)	S (MPa)	R (MPa)	Q (MPa)
1328	1064	70.9	221	97.6	242	71.2	94.5	52.9

The plates were polymerised under a pressure of 7 bars at a temperature of 180°C for tow hours. And then three different cooling conditions were imposed:

Condition **A** (fast cooling) : the specimens have been immersed in cold water during 3 minutes as soon as the plates were polymerized ;
Condition **B** (normal cooling) : the specimens removed from the mould were cooling at room temperature ;
Condition **C** (slow cooling) : after the press was extinct, the specimens were hold in the mould under the press.

These cooling conditions must produce different residual stresses in laminates especially between the plies 0° and 90°. The laminates obtained are then cut and used for the residual stress measurement, and the tensile tests were carried out to investigate the mechanical behavior with presence of different residual stresses.

DETERMINATION OF RESIDUAL STRESSES

Experimental measurement

Hold-drilling method with the help of strain gages was originally developed for homogeneous and isotropic materials to determine uniform and non-uniform residual stresses in depth [11]. This method consists in establishing the relationship between the variation of surface strains due to hole-drilling and residual stress distribution, where two independent calibration coefficients have been introduced. Bert [12] and Lake [13] have extended this method to orthotropic materials by introducing three independent calibration coefficients. Afterwards, Prasad et al. [14] and Schajer et al. [15] have developed an analytic through-hole solutions. In these methods, only through-holes are drilled and an uniform distribution of residual stress throughout the thickness was assumed. However, in a multidirectional laminated composite, residual stresses in tension and compression can be found alternately in different plies and thus the above through-hole methods were obviously unsuitable.

In order to measure experimentally the residual stresses distribution in thickness, rosette gages were placed on 0°, 135° and 225° in surface of laminate (Fig.1). The drilling process was controlled accurately by a computer program. The translation speed of the drill bit was 2 μm per second to avoid interface delamination. The diameter of the drill bit used in the experiment is 2 mm, 8 steps of a hole-drilling process with an identical increment of 62.5 μm (½ ply) were performed successively to the half thickness of the laminate because of laminate symmetry (8 steps x 0.0625 mm = 0.5 mm = half specimen thickness). The calibration coefficients determined by an element analysis can be used directly in the experiment. The response of strain gages corresponding to each hole drilling step is recorded as ε_n^1 (θ=0°), ε_n^2 (θ=225°) and ε_n^3 (θ=135°).

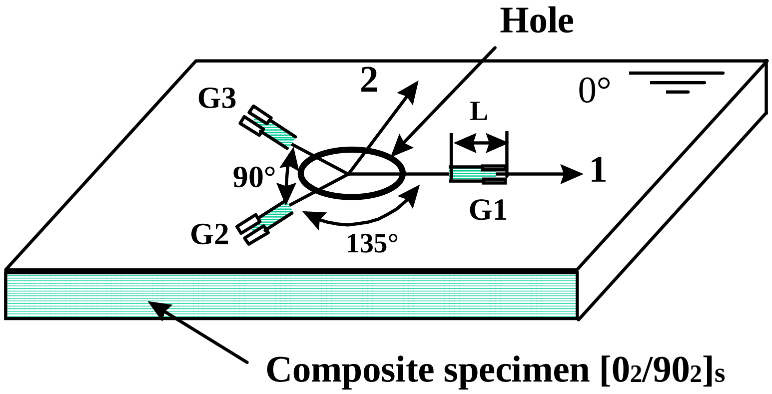

Fig.1 : Specimen and rosette gage instrumentation

Figure 2 gives the variation of micro strains ε_n^1 for three cooling conditions A, B and C with a function of hole-drilling depth. It can be seen that the residual stresses are more significant in the case of fast cooling (condition A) than that in the case of slow cooling (condition C). In order to convert measured strains into residual stress distribution in laminate, a numerical model based on the finite element method is proposed to determine several constants necessary to convert the variation of residual stress distribution into laminate.

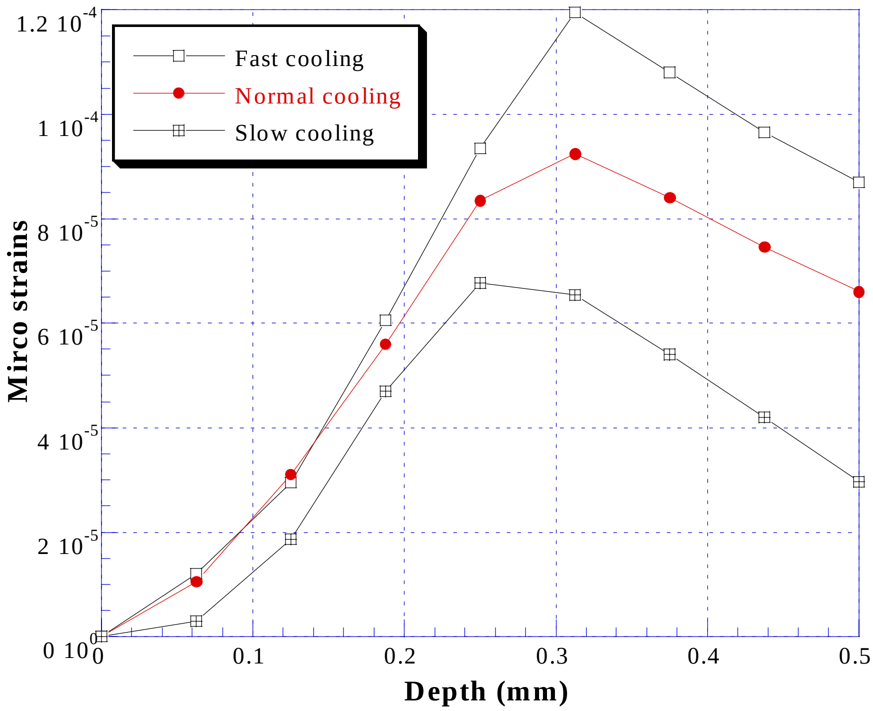

Fig.2 : Micro-strain in surface ε_n^1 (θ=0°) obtained by the incremental hole-drilling method for three cooling conditions

Approximation solution for orthotropic materials

A model for determination of the distribution of residual stresses in laminates is developed for incremental hole-drilling method, it is based on the following conditions :

- the material is elastic and orthotropic for each ply ;
- the components of stress in planes perpendicular to the surface are very small ;
- strains on the surface have to be measured in three radial directions.

Let the depth of each ply i be h_i, the principal stresses in ply i be σ_{1i} and σ_{2i}, the number of the plies be n. The radial strains corresponding to the principal residual stresses can be expressed by :

$$\varepsilon_{in}(\theta_i) = A_{in}(\sigma_{1i} + \sigma_{2i}) + B_{in}[(\sigma_{1i} - \sigma_{2i})\cos 2\theta_i \qquad (1)$$

where the coefficient A_{in} and B_{in} are a function of the radius r, the ply position and the total depth of the hole. Radial strains on the surface are measured at each increment n by the set of three strain gages ε_n^1, ε_n^2 and ε_n^3, from which the three unknowns at nth increment (principal stresses σ_{1n} and σ_{2n} and principal direction θ_n) can be calculated by the equation 2 :

$$\begin{cases} \sigma_{1n} = \dfrac{\left(\varepsilon_n^1 - \sum\limits_{i=1}^{n-1}\varepsilon_{in}^1\right)\left(A_{nn} + B_{nn}\sin 2\theta_n\right) - \left(\varepsilon_n^2 - \sum\limits_{i=1}^{n-1}\varepsilon_{in}^2\right)\left(A_{nn} - B_{nn}\cos 2\theta_n\right)}{2A_{nn}B_{nn}\left(\sin 2\theta_n + \cos\theta_n\right)} \\ \sigma_{2n} = \dfrac{\left(\varepsilon_n^2 - \sum\limits_{i=1}^{n-1}\varepsilon_{in}^2\right)\left(A_{nn} + B_{nn}\cos 2\theta_n\right) - \left(\varepsilon_n^1 - \sum\limits_{i=1}^{n-1}\varepsilon_{in}^1\right)\left(A_{nn} - B_{nn}\sin 2\theta_n\right)}{2A_{nn}B_{nn}\left(\sin 2\theta_n + \cos\theta_n\right)} \\ \theta_n = \dfrac{1}{2}arctg\left(\dfrac{\varepsilon_n^1 - \sum\limits_{i=1}^{n-1}\varepsilon_{in}^1 - 2\varepsilon_n^2 + 2\sum\limits_{i=1}^{n-1}\varepsilon_{in}^2 + \varepsilon_n^3 - \sum\limits_{i=1}^{n-1}\varepsilon_{in}^3}{\varepsilon_n^1 - \sum\limits_{i=1}^{n-1}\varepsilon_{in}^1 - \varepsilon_n^3 + \sum\limits_{i=1}^{n-1}\varepsilon_{in}^3}\right) \end{cases} \quad (2)$$

where $\sum\limits_{i=1}^{n-1}\varepsilon_{in}^1$, $\sum\limits_{i=1}^{n-1}\varepsilon_{in}^2$, $\sum\limits_{i=1}^{n-1}\varepsilon_{in}^3$ are the part of the total strains on the surface. These strains in three strains gages direction are obtained from stress values calculated in higher layers (equation 1). In practice, it is here necessary to determine all coefficients A_{in} and B_{in} .

Determination of Calibration Coefficients

Calibration coefficients A_{in} and B_{in} can be determined by using a finite element analysis. This method consists in calculating the in-plane surface displacements produced by incremental hole drilling, an iterative procedure of loading is used. Analyzing the increment fields of these displacements and using the development in Fourier series of the expansion solution, we can establish the relation between strains of surface around the hole and the corresponding residual stresses in each ply of the composite laminate.

In the case of an isotropic homogeneous continuum, in-plane uniform residual stresses are assumed, we can obtain a theoretical through-hole solution expressed as:

$$u_{in}(r,\theta_i) = A_{in}(\sigma_{1i} + \sigma_{2i}) + B_{in}(\sigma_{1i} - \sigma_{2i})\cos 2\theta_i] \quad (3)$$

In order to determine the calibration coefficients a three dimensional finite element model is implemented in implicit Abaqus-software. The coefficients A_{in} can be determined by applying a normal residual pressure boundary $\sigma_{1i} = \sigma_{2i} = \sigma$ and $\sigma_{3i} = \sigma_{12i} = 0$ which is equivalent to the harmonic distributions of the normal stress acting on each ply. Similarly, the coefficients B_{in} can be determined by shear residual stress field boundary $\sigma_{1i} = -\sigma_{2i} = \sigma$ and $\sigma_{3i} = \sigma_{12i} = 0$. For each ply i and each increment n, the coefficients A_{in} and B_{in} can be obtained by :

$$A_{in} = \frac{u_{in}(r_2,\theta_n) - u_{in}(r_1,\theta_n)}{2\sigma} \quad B_{in} = \frac{u_{in}(r_2,\theta_n) - u_{in}(r_1,\theta_n)}{2\sigma\cos 2\theta_n} \quad (4)$$

where $u_{in}(r_1,\theta_n)$ and $u_{in}(r_2,\theta_n)$ are radial displacements at the beginning and at the end of the working length of the strain-gages.

Laminates studied in this work are orthotropic ones with a stacking sequence of $[0_2/90_2]_s$. The model described above can be extend to our case. We consider that each ply has an average thickness of 0.125 mm. A blind-hole was introduced incrementally with an identical increment of 0.0625 mm. Regarding the symmetry of the laminate structure, only half the thickness of eight plies from one side of the laminate is studied. The diameter of the drill bit used in the experiment was 2 mm.

Figure 3 shows the distribution of residual stresses in the laminates studied. Note that the residual stresses are in compression in plies 0° and in tension in plies 90° and the influence of the cooling conditions on the internal stresses in laminates seems evident. In the case of fast cooling, the maximal residual stress is about 170 MPa , whereas for the normal and slow cooling conditions, the residual stress is 97 MPa and 87 MPa, respectively.

Recall that the tension strength of the material in the direction of 90° is about 70 MPa, the maximal residual stress obtained by this elastic analysis is too high to be true. In fact, it is possible that the damage in 90° plies has occurred during cooling because of high residual stress, the damage process and the redistribution of stress so has to be considered for calculating the true residual stress in material induced by cooling condition.

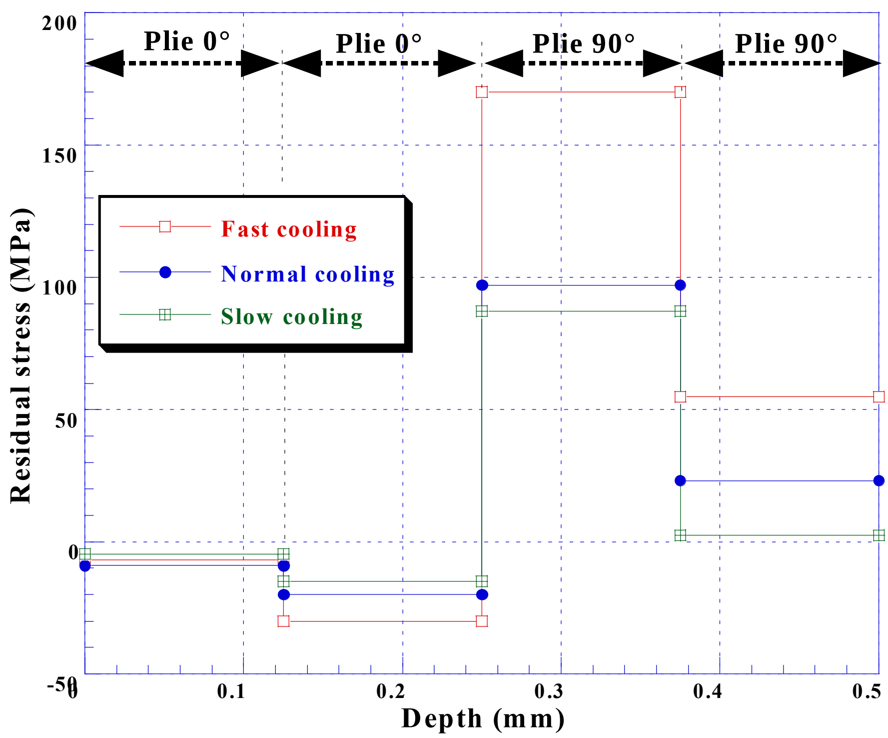

Fig.3 : Distribution of residual stresses σ_1 (0°) versus depth of specimen thickness

TENSION TESTS AND DISCUSSION

Specimens and test conditions

Specimens were cut from the $[0_2\ /90_2]_S$ laminates (fibre direction 0° in the length of specimens). The dimensions of all specimens were 150mm x 15mm x 1 mm. The specimens were loaded with the help of the tabs attached at ends .

The tensile tests were carried out in a static tension machine at room temperature with an imposed displacement rate of 1 mm/min. An extensometer with a 12.5 mm initial opening length was placed at the centre of specimens. The displacement δ measured would be used to obtain the average deformation $(\varepsilon_{clip})_j$ by the relationship : $(\varepsilon_{clip})_j = (\delta_j - \delta_{j-1}) / (12.5 + \delta_{j-1})$, here j represents successive measures of the extensometer during tension loading. The specimens were also instrumented by an acoustic emission receptor so as to detect damage initiation.

The following experimental information was recorded simultaneously during the tests : applied load (P), displacement of the extensometer (δ) and acoustic emission (cumulative counts).

Results and discussion

Figure 4 shows the experimental curves of tensile tests for three cooling conditions associated with acoustic emission signal. Apparent stresses are determined by dividing the load by specimen section.

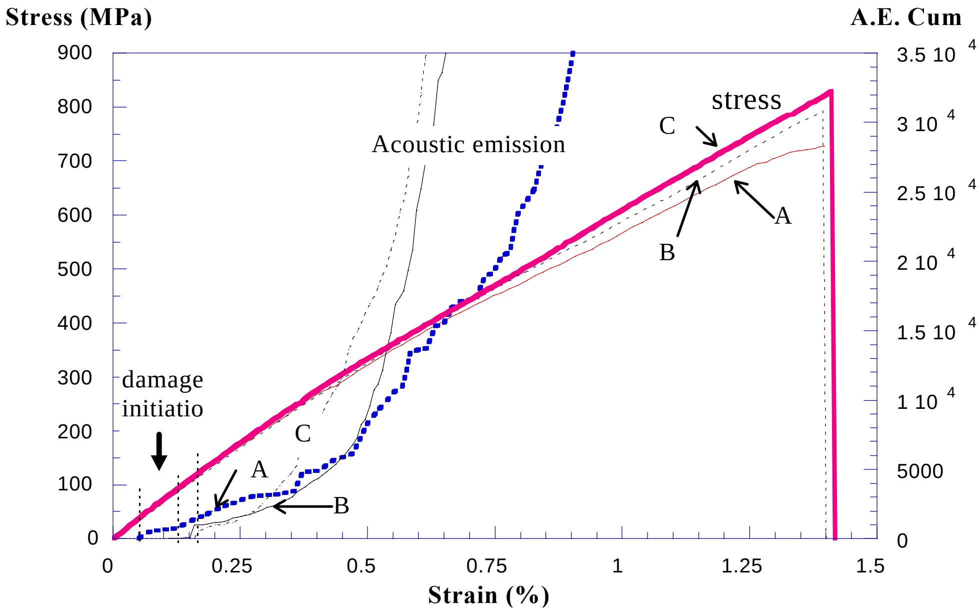

Fig.4 : Apparent stresses and Acoustic emission versus strains
for different cooling conditions A, B and C

The principal results are listed in table 2, where each value is an average of measurement of six specimens.

Table 2 : Results of tension tests (A,B and C)

	E_{ini} (GPa)	$\sigma_{A.\ Fracture}$ (MPa)	$\sigma_{A.\ Damage\ Ini}$ (MPa)	$\varepsilon_{Fracture}$ (%)
A	66.2±0.18	735.5±4.4	51.2±3.2	1.39±0.09
B	66.0±0.15	792.8±3.5	104.1±2.9	1.40±0.08
C	66.4±0.21	827.0±3.9	128.4±5.3	1.42±0.10

It is interesting to noted that :

1) initial Young's modulus are almost identical for the three cooling conditions, the presence of the residual stresses seems no effect on initial stiffness of material. We can see that the deviation of the curves starts from certain load, which is considered as damage initiation, very different for three cooling conditions. After that, the material stiffness decreases, more important is residual stress, more rapidly the stiffness decreases.
2) a difference of apparent fracture stresses ($\sigma_{A.\ Fracture}$) among three cooling conditions is observed. The value for fast cooling condition is about 11% lower than that for slow cooling condition. The damage level of 90° plies seems responsible.
3) damage initiation can be detected by the appearance of the acoustic emission. The difference of the apparent initiation damage stresses ($\sigma_{A.\ Damage\ Ini}$) detected by acoustic emission between the three cooling conditions is more significant, the apparent damage stress in the case A is only 40% of that in the case C. We feel that the presence of the residual stresses plays an role more important.
4) failure strains are identical for the three cooling conditions (1.4% approximately). In the first estimation of laminate strength, failure strain is perhaps a useful parameter.

CONCLUSIONS

The distribution of residual stresses in 0°-90° laminates is not uniform, σ_1 in compression for the plies 0° and in tension for 90°. A sudden change from negative to positive occurs in the adjacent plies 0-90° (Fig.3).

The tensile tests allow to evaluate the macroscopic behavior of material with the presence of the residual stresses. For the three cooling conditions, the initial elastic modulus are the same ones and the failure strain is also identical.

The apparent failure stresses and damage initiation stresses have to be added by residual stresses to obtain material strength. In order to obtain true residual stresses in material induced by fabrication condition, we need a more sophisticated model which can take into account damage process, relaxation and distribution of stresses in laminates with a function of temperature during cooling.

In prospect, the shear residual stress τ_{12} must be determined. The torsion and combined traction and torsion tests have to be developed for application of a criterion in the case of complex loading condition with the presence of residual stresses.

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